CGMS-52-IROWG-WP-01
02 April 2024

Prepared by: IROWG
Agenda Item WGII/3.3
Discussed at WGII

Subject	**IROWG UPDATE ON RECOMMENDATIONS AND ACTIVITIES**
In response to CGMS action/recommendation	N/A
HLPP reference	N/A
Executive Summary	The IROWG community has not held a workshop since CGMS-51. The next workshop, IROWG-10, is planned for 12-18 September, 2024 on the University Corporation for Atmospheric Research (UCAR) campus in Boulder, Colorado, United States. The IROWG leadership and chairs and co-chairs of the four sub-groups met virtually on February 26, 2024 to discuss updates since CGMS-51. Actions since CGMS-51 were reviewed. Updates were discussed in the following areas, described in more detail later in this document: ● Update on projected number of radio occultations (RO) ● Long-term archiving of level 0 (raw) data ● Best Practices document on a backbone RO constellation for climate studies ● Recent studies on RO impact to numerical weather prediction (NWP) ● Progress within the RO Modeling Experiment (ROMEX) ● Updates to the BUFR format ● Topics possibly leading to future recommendations IROWG will convene a ROMEX workshop on April 17-19 at EUMETSAT, Darmstadt, Germany. During this event, meeting minutes and a summary presentation will be compiled for submission to CGMS.
Action/Recommendation proposed	N/A

1 INTRODUCTION

The IROWG community has not met since CGMS-51. The IROWG leadership and chairs and co-chairs of the four sub-groups met virtually at an intersessional meeting on February 26, 2024 to discuss updates since CGMS-51. Actions since CGMS-51 were reviewed. What follows is a report on updates discussed at the intersessional, and a description of the upcoming IROWG-10 workshop planned for September 12-18 in Boulder, Colorado.

IROWG will convene a radio occultation (RO) Modeling Experiment (ROMEX) workshop on April 17-19 (the week before the CGMS-52 WG meeting) at EUMETSAT, Darmstadt, Germany. During this event, meeting minutes and a summary presentation will be compiled as supplementary materials to this working paper for submission to CGMS-52.

2 UPDATE ON PROJECTED NUMBER OF RO

IROWG continues to monitor the number of real-time GNSS (Global Navigation Satellite System, e.g. GPS) RO observations available to numerical weather prediction (NWP) operational centres through the WMO GTS server. During the intersessional meeting, Christian Marquardt of EUMETSAT provided an update on the projected number of daily RO profiles from government-led systems, reflecting new expected launch dates for the satellite missions containing RO measurements recognized by CGMS-51. Estimates of the number of commercially-provided RO are also shown for NOAA and EUMETSAT purchases of globally licensed data. We acknowledge that these estimates for commercially-provided data do not reflect ongoing purchases through 2024 and beyond. The graphical representation is below (Figure 1).

Due to the significant number of profiles provided by the COSMIC-2 constellation, which are not globally distributed but limited to latitudes between ± 40°, Figure 1 may appear to overestimate how close the numbers are to the IROWG and HLPP targets of 20,000 per day of *globally distributed* profiles.

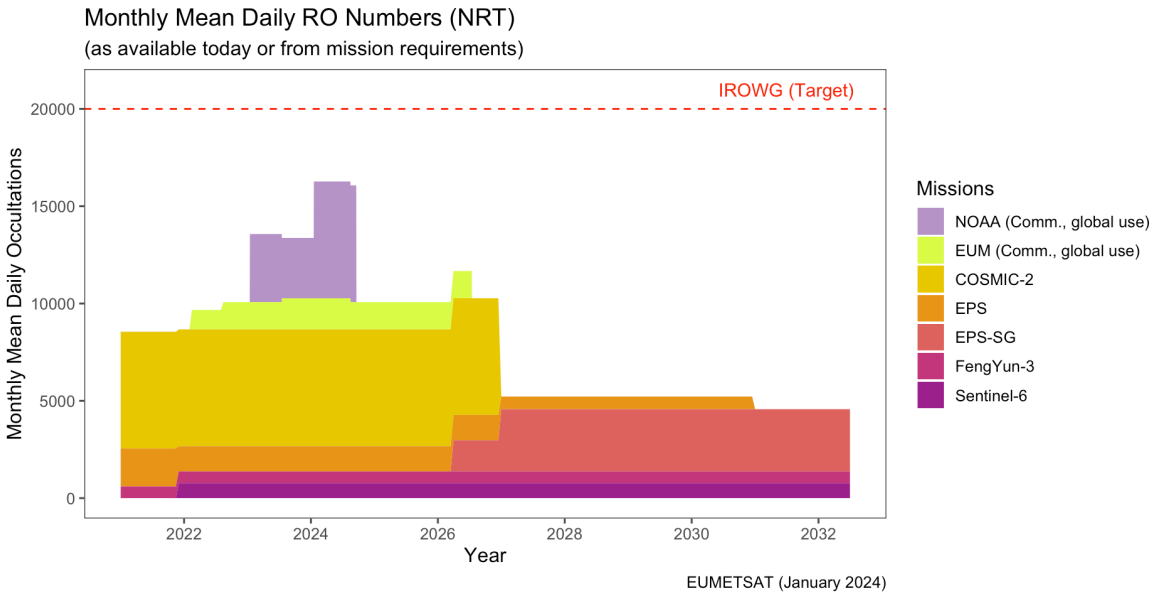

Figure 1: graphical representation of the monthly mean number of daily RO profiles provided by different government systems and commercial data buys. Courtesy of EUMETSAT.

The data of Figure 1 highlight a significant risk beyond the lifetime of the COSMIC-2 mission (brown-gold color in Figure 1). Government-supported systems are expected to experience a substantial reduction in the number of provided occultation profiles due to limited missions and resources. Given the uncertainties surrounding government commercial purchases, licensing for worldwide distribution, local time distribution and other data maintenance and processing issues (such as distributed and diverse data archiving and processing), IROWG seeks to emphasise to CGMS the scientific benefits of government-led backbone satellite systems. At the same time, there is a need to continue coordinating commercial data purchases and addressing related data archiving and processing challenges. Some of these issues were discussed during the intersession meeting and are documented in the following sections.

3 DATA ARCHIVING

The chair of the Receiver Technology and Innovative RO Techniques sub-group, who works for a commercial provider of RO data to NOAA, brought to the attention of the intersessional meeting that commercial providers may be expected to archive the raw data that are purchased. This led to a discussion of, and concerns regarding, decentralised approaches to long-term data archiving, where responsibilities may be distributed between government and commercial sectors. This matter is further discussed in Section 8.

4 BACKBONE RO CONSTELLATIONS

CGMS agencies are currently assessing the desirability of maintaining government owned and operated “backbone” observing systems in the context of hybrid observing system architectures that include small satellites and commercial data buys (e.g. see CGMS-51 Plenary action item A51.08). As an outcome of IROWG-9, an operational GNSS-RO constellation was recommended as part of the backbone. IROWG has produced a Best Practices (BP) draft document “IROWG best practices in support to radio occultation observations for long-term climate studies” that started within the climate sub-group but that also applies to numerical weather prediction applications. The BP draft will be presented for discussion at the CGMS-52 WGII meeting.

It was also noted that NOAA is considering RO backbone constellations in future satellite planning. NOAA’s National Environmental Satellite, Data, and Information Service Systems Architecture and Engineering Office (NESDIS SAE), in collaboration with the University Corporation for Atmospheric Research (UCAR), has launched a project in the past four-months to conduct a GNSS-RO backbone infrastructure study. This project “aims to provide initial insight into potential system architectures to follow the FORMOSAT-7/COSMIC-2 (COSMIC-2) mission and provide RO observations for operational weather and space weather applications, climate studies, and the broader research community”. With specifically defined key requirements, the project presents the infrastructure baseline needed to meet these requirements, along with estimated costs associated with various scenarios. This report is available upon request to NOAA. While this initiative takes place outside the IROWG workshops, the IROWG welcomes such endeavours from CGMS partners and agencies that engage in backbone mission studies. These activities have the potential to address the risks arising from the lack of government-supported RO observation efforts over the next decade (section 8.3).

5 RECENT RO IMPACT RESULTS

During the intersession meeting, IROWG sought information from its subgroups regarding GNSS-RO impact studies. The Chair of IROWG's NWP sub-group mentioned ongoing impact studies at the UK Met Office, which served as a precursor to ROMEX experiments. A graphical representation of this study is provided below (Figure 2). The study evaluates performance over two years by analysing the mean changes in scorecard versus observations and ECMWF analysis after assimilating specific types of observations. The ranking of these observation types illustrates their respective contributions to forecast improvement.

The 2023 results show an improvement in GNSS-RO impacts, moving from the 5th place to the 4th place in the ranking when compared against other observations, and from the 3rd place to the 2nd place when compared against ECMWF analysis. This improvement is primarily attributed to increased GNSS-RO data volumes. This result validates the findings presented in the IROWG’s CGMS-49 report, which were based on ECMWF results. It illustrates the increase in GNSS-RO impact when commercial

data are integrated into the ECMWF operational systems, resulting in enhanced coverage and a higher number of GNSS-RO observations within the system, thereby leading to improved weather forecasts.

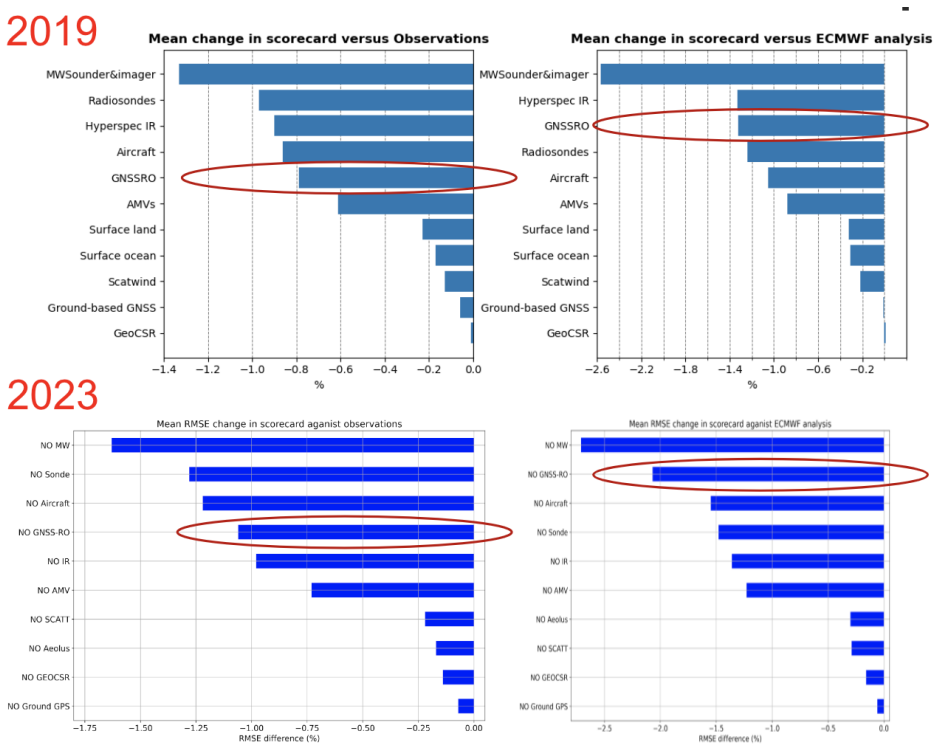

Figure 2: Mean root-mean-squared-error (RMSE) changes in scorecard against observations (left) and the ECMWF analysis (right) calculated from the observation denial experiments performed in 2019 (upper panel) and 2023 (lower panel) by the UK Met Office.

6 UPDATE ON THE RADIO OCCULTATION MODELING EXPERIMENT (ROMEX)

Participants at the intersessional meeting confirmed that IROWG continues to support the previous recommendation that GNSS-RO data - with at least 20,000 occultations per day - are globally distributed and provide full sampling of the diurnal cycle (local time). This is important for NWP, Climate, and Space Weather. IROWG also recommends further investigation of the value of increased target observation quantities, to provide a sound basis for future statements on the desirable number of observations and insights on satellite mission planning and coordination.

Additionally, IROWG advocates for further examination of the potential benefits of increasing the quantity of profiles available for NWP. Consequently, IROWG-9 endorsed a collaborative initiative named the Radio Occultation Modeling Experiment (ROMEX), which involves over 20 international data providers, processing centres, NWP centres, and research institutes. This investigation aims to establish a solid

foundation for determining the optimal number of observations, offering valuable insights for satellite mission planning and coordination.

Following IROWG-9, a ROMEX steering committee was established, comprising the following members:

- Hui Shao, Joint Center for Satellite Data Assimilation (JCSDA) and IROWG co-chair
- Rick Anthes, UCAR
- Christian Marquardt, EUMETSAT
- Benjamin Ruston, JCSDA

Since its formation, the committee has convened numerous meetings with data providers, data processing centres, and NWP centres to delineate the scope of ROMEX, address pertinent issues, and resolve conflicts. IROWG has established a ROMEX webpage and is providing a white paper along with other relevant information to the community. EUMETSAT and its Radio Occultation Meteorology Satellite Application Facility (ROM SAF) have graciously agreed to be the primary entities responsible for collecting and hosting ROMEX data, as well as providing additional processing as necessary. JCSDA has assumed the responsibility of orchestrating the group discussions and facilitating online meetings. Both the UK Met Office and the German Weather Service (DWD) have committed to spearheading the initiatives concerning the exchange of validation results and the development of verification metrics. Meanwhile, UCAR/COSMIC and NESDIS expressed their willingness to contribute by offering supplementary data processing capabilities through their proprietary in-house software. This contribution aims to enhance understanding regarding data processing methodologies, retrieval processes, and the quality of observations across various satellite missions.

Figure 3: ROMEX-Daily observation data count. Additional missions not shown yet in the plot: GeoOptics, TerraSar-X, Tandem-X, Kompsat-5, and Tianmu.

Through collaborative efforts with various centres and data providers, ROMEX has amassed a three-month dataset encompassing approximately 36,000 profiles per day (Figure 3), representing a substantial increase compared to current operational capabilities. The initial version of ROMEX data was released to the ROMEX community in January 2024, comprising users who have agreed to the data user Terms and Conditions. IROWG will organise a ROMEX Workshop sponsored by EUMETSAT on April 17-19, 2024, in Darmstadt, Germany. During this event, agencies and researchers will present their progress and plans for ROMEX. Meeting minutes and a summary presentation will be compiled as supplementary materials to this working paper for submission to CGMS-52.

7 UPDATE ON THE BUFR FORMAT

The intersessional meeting followed up on the internal action items from IROWG-9. Among these directives was the formation of a sub-committee tasked with exploring a potential revision to the BUFR format. IROWG-9 reiterated the imperative to incorporate supplementary data into the GNSS-RO BUFR template. Notably, the NWP subgroup underscored the necessity for including receiver IDs and a measure of Signal-to-Noise Ratio (SNR). Moreover, this updated template should be adaptable to novel techniques and observation types, such as airborne GNSS-RO (ARO) and polarimetric GNSS-RO (PRO).

The consensus reached during IROWG-9 was to proceed with defining a new GNSS-RO template, notwithstanding ongoing deliberations regarding specifics and elements. Subsequently, a sub-committee dedicated to reformatting the GNSS-RO BUFR template was established, culminating in an on-site meeting. Following this initial gathering, regular online meetings have been conducted under the co-leadership of Neill Bowler (UK Met Office, NWP subgroup co-chair) and Hui Shao (JCSDA, IROWG co-chair).

Consequently, a revised BUFR template for GNSS-RO has been proposed, consolidating templates for various types of RO data (RO, ARO, PRO) and facilitating the incorporation of additional observation types, information, and/or retrieved properties (e.g., local spectral width, atmospheric ducting flag) into the template. The subcommittee intends to present the new BUFR template at the forthcoming IROWG-10. Concurrently, the subcommittee continues to finalise the proposal while soliciting suggestions and expert guidance on BUFR (e.g., Jeff Ator at NOAA and Simon Elliott at EUMETSAT).

8 TOPICS THAT MAY LEAD TO ACTIONS AND/OR RECOMMENDATIONS FOR CONSIDERATION BY CGMS

Given that the following topics have not yet undergone full discussions within the IROWG community and recognizing that IROWG-10 is expected to provide the platform for such discussions, we present these topics as possibly leading to formal recommendations following IROWG-10**.**

8.1 Data Archiving

During the intersession meeting, IROWG reiterated its appreciation to NOAA and EUMETSAT for upholding an open data policy concerning the procurement of commercial RO data and further advocated for all agencies to adopt this approach. Emphasising the critical nature of unfettered access to essential RO data, including both current and archived raw or low-level (level 0) data, IROWG highlighted the necessity for maintaining this accessibility.

Additionally, the intersessional meeting underscored the importance of addressing the coordination of low-level (level 0) commercial data archives among agencies and data providers within the CGMS agencies. It was acknowledged that while some government contracts stipulate that commercial companies establish archives, others entrust data archiving to government-owned archive centres. The varying and decentralised approaches to archiving may pose potential risks to the long-term preservation of climate-quality GNSS-RO observations. The importance of data archiving is emphasised in one of the recommendations for CGMS members from CGMS-51 Working Group II (WGIIR50.4) (emphasis added): “All providers of RO observations are encouraged to classify RO data as core data in the sense of the WMO Unified Data Policy (Res. 1). Therefore, free, timely and unrestricted access shall be provided to near real-time (NRT) RO data and **free and unrestricted access shall be provided to archived raw data (including auxiliary data)”**. The WGII recommendation is aligned with a recommendation put forth by IROWG-9, specifically, "IROWG strongly supports an open data policy towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG stresses the importance of free and unrestricted access to essential RO data including archived raw or low-level (level 0) data."

Heterogeneity in archival responsibilities and practices will be a topic of discussion at IROWG-10, with the intent to provide recommendations to CGMS, should the need arise.

8.2 Technology for Boundary Layer Profiling

A recommendation to CGMS from IROWG-9 was related to improving utilisation of RO measurements in the planetary boundary layer, which generally occupies the lowest

2-3 km of the atmosphere. The recommendation, originating in the “Receiver Technology and Innovative Occultation Techniques” sub-group, is:

- IROWG encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation as well as the further exploitation of RO-derived water vapour.

At CGMS-51, WGII, it was suggested that the recommendation will have more effectiveness if specific use cases are developed and presented to the NWP centres. Discussion of such cases will be put on the agenda for IROWG-10 and will be reported at CGMS-53.

8.3 Address the risk of inadequate sustained RO observation efforts over the next decade.

In responding to the top-level risk assessment of Earth Observations conducted by CGMS WGIII in 2023 (Figure 4), IROWG remains vigilant in monitoring the evolution of RO observation systems. Moreover, IROWG aims to draw CGMS' attention to the following points:

- IROWG continues to advocate for and support the recommendations outlined in IROWG-9 - IROWG recommends operational GNSS-RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.
- It is imperative for CGMS to recognize the potential risks associated with the lack of future planning for low-inclination RO observations after COSMIC-2. Notably, NOAA's backbone study provides valuable infrastructure guidelines to fulfil the desired RO capabilities, underscoring the significance of such initiatives and coordination among CGMS agencies.
- Moreover, there are risks associated with the commercial purchase of RO data, particularly concerning spatial-temporal coverage, data continuity and data archiving (as discussed in Section 8.1). The sustainability of such efforts raises significant concerns regarding the use of commercial data. Therefore, it is essential for stakeholders to address these risks proactively to ensure the continued success and effectiveness of use of RO observations.

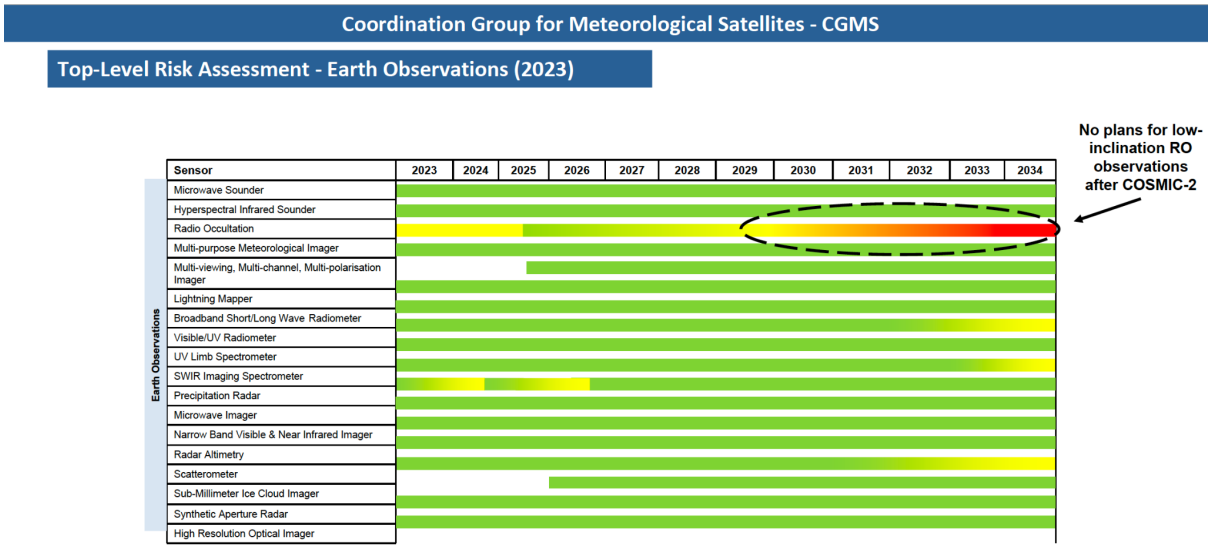

Figure 4: Top level risk assessment of Earth Observations. The risk is highest for radio occultation observations. (A. Mehta, CGMS WGIII report, 2023)

9 PROPOSED IROWG-10 SETUP

The next IROWG workshop (IROWG-10) will be held on September 12-18, 2024 in Boulder, Colorado, on the UCAR campus. It will be jointly hosted by the Joint Center for Satellite Data Assimilation and the UCAR COSMIC program, and sponsored by various entities (final sponsor list will be provided once the program is finalised). The web site for the workshop is at:

https://www.cosmic.ucar.edu/events/cosmic-jcsda-workshop-irowg-10

IROWG-10 will be a full workshop, including presentations, posters, sub-group discussions and social activities. The presentations/posters and the sub-groups will be organised according to the following specific topics, namely:

Numerical Weather Prediction (NWP);
Climate;
Receiver Technology and Innovative Occultation Techniques;
Space Weather.

Additionally, the workshop will feature special ROMEX sessions aimed at constructing a ROMEX report.

As for all IROWG workshops, IROWG-10 participants will be asked to summarise relevant activities within the scope of the sub-group in dedicated sub-group meetings and express recommendations which could either be relevant to CGMS, to the GNSS-RO community, to providers of RO data, or within the IROWG. Recommendations will

be discussed in the open plenary. Furthermore, the sub-groups will assess the status of the relevant CGMS actions and follow up on internal recommendations/actions.

10 CONCLUSIONS

The IROWG community has not held a workshop since CGMS-51. Therefore, we re-state the four key recommendations previously presented at CGMS-51, endorsed by the IROWG community at IROWG-9, held on September 8-14, 2022 in Leibnitz, Austria:

(1) IROWG strongly supports an open data policy towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG stresses the importance of free and unrestricted access to essential RO data including archived raw or low-level (level 0) data.

(2) IROWG recommends operational Global Navigation Satellite System (GNSS) RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.

(3) IROWG continues to support the previous recommendations that GNSS-RO data - with at least 20,000 occultations per day - are globally distributed and provide full sampling of the diurnal cycle (local time). This is important for NWP, Climate, and Space Weather. IROWG also recommends further investigation of the value of increased target observation quantities, to provide a sound basis for future statements on the desirable number of observations and insights on satellite mission planning and coordination.

(4) IROWG recognizes the importance of space weather applications of RO data. IROWG recommends that RO and non-RO missions that use dual-frequency GNSS receivers for their orbit determination needs should make available to the operational and research communities all necessary low-level (level 0) data and metadata required to produce accurate overhead TEC data from the GNSS receiver.

(5) IROWG encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation as well as the further exploitation of RO-derived water vapour.

The IROWG leadership and chairs and co-chairs of the four sub-groups met virtually on February 26, 2024 to discuss updates since CGMS-51. Actions since CGMS-51 were reviewed. Updates were discussed in the following areas:

Projected number of RO: There is high potential risk associated with the lack of future planning for low-inclination RO observations beyond the lifetime of the COSMIC-2

mission. Moreover, there are risks associated with the commercial purchase of RO data, particularly concerning spatial-temporal coverage, data continuity and data archiving. Notably, NOAA's backbone study provides valuable infrastructure guidelines to fulfil the desired RO capabilities, underscoring the significance of such initiatives and coordination among CGMS agencies.

Best Practices: IROWG has produced a Best Practices (BP) draft document “IROWG best practices in support to radio occultation observations for long-term climate studies” that will be presented for discussion at the CGMS-52 WGII meeting.

Recent RO impact results: At the UK Met Office, 2023 results show an improvement in GNSS-RO impacts, moving from the 5th place to the 4th place in the ranking when compared against other observations, and from the 3rd place to the 2nd place when compared against ECMWF analysis. This improvement is primarily attributed to increased GNSS-RO data volumes.

The Radio Occultation Modeling Experiment (ROMEX): Through collaborative efforts with various centres and data providers, ROMEX has amassed a three-month dataset encompassing approximately 36,000 profiles per day. The initial version of ROMEX data was released to the ROMEX community in January 2024. IROWG will organise a ROMEX Workshop sponsored by EUMETSAT on April 17-19, 2024, in Darmstadt, Germany. During this event, agencies and researchers will present their progress and plans for ROMEX. Meeting minutes and a summary presentation will be compiled as supplementary materials to this working paper for submission to CGMS-52.

BUFR format revision: A sub-committee was formed to explore a potential revision to the BUFR format for including receiver IDs and a measure of Signal-to-Noise Ratio (SNR). Moreover, this updated template should be adaptable to novel techniques and observation types, such as airborne GNSS-RO (ARO) and polarimetric GNSS-RO (PRO).

Data archiving: The intersessional meeting underscored the importance of addressing the coordination of low-level (level 0) commercial data archives among agencies and data providers within the CGMS agencies. Varying and decentralised approaches to archiving may pose potential risks to the long-term preservation of climate-quality GNSS-RO observations. Heterogeneity in archival responsibilities and practices will be a topic of discussion at IROWG-10, with the intent to provide recommendations to CGMS, should the need arise.

The next IROWG workshop (IROWG-10) will be held on September 12-18, 2024 in Boulder, Colorado, on the UCAR campus. It will be jointly hosted by the Joint Center for Satellite Data Assimilation and the UCAR COSMIC program, and sponsored by various entities (final sponsor list will be provided once the program is finalised). The web site for the workshop is at:

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